normal replacement of equipment.

83. *Possible extra-spectrum assignments.* Since we favor phasing out NTSC, we support the option of an extra 6 MHz for an independent HDTV signal.

83, 84. *6 MHz only?* The single-channel ATV systems will not provide any improvement in performance over NTSC with respect to channel degradation; in fact, they may be worse. It might be possible to get a wide picture, but since the side panels will be devoid of significant information, the aesthetic effect will be very small. About as good results would be obtained with IDTV or Faroudja's scheme. I believe that all HDTV systems will cost about the same. (See Section 4.2) A system that does not cost the broadcaster or the consumer very much will not improve reception enough to make it worth while.

85. *Effect of compatibility on speed of transition.* There is absolutely no evidence that there will be a high demand for compatible ATV receivers; in fact, I think just the opposite is likely and that going the compatible route will result in very slow growth of ATV. This was the case with color, and we should realize that ATV has a much smaller impact than color. See Section 4.3.

86. *Competition with alternative media.* No NTSC-based format, no matter what the bandwidth, can provide pictures of the typical quality available to other media using a more robust and necessarily noncompatible format.

87. *3 MHz augmentation.* Under good channel conditions, this scheme can provide about MUSE quality. Such a system is described in Appendix 2. However, under typical channel conditions, the quality will be not much better than we see at home right now, and there would be no possibility of reducing the total spectrum allocated to TV unless the scheme were abandoned at a later date.

88. *Cost of an augmentation channel.* This cost would be quite low, since the Zenith approach could be used. Since the taboo channels would be used, there would be no reduction in anyone's service area. However, there is a question as to whether this is a good stepping stone to an ultimate system. See Appendix 2 and Section 4.

89. *6 MHz augmentation for a separate signal.* This is the best approach, in our opinion. If the Zenith, MIT, or some combination thereof can perform as proposed, and we have ATV in low-power 6-MHz channels, NTSC will eventually fall of its own weight.

90. *Desirability of 6 MHz extra.* This is the best choice, in our opinion. Its feasibility depends entirely on the interference performance of the proposed systems, and this, presumably, can be readily tested. Transition to a totally new

system does call for expenditures by broadcasters, but it also gives them a fair shake at meeting the competition of alternative media. Variants of these systems can be used in all media, so there is the possibility of friendly, if not identical, formats.

91. *Cost and benefits of ATV vs more stations.* As pointed out in the main body of my comments, it appears to be technically feasible to have the best of both worlds — more medium-definition signals part of the time, and fewer ATV transmissions at other times. This would permit choosing the format on the basis of what is to be transmitted, and saving ATV for special subjects that need the resolution. 500-line TV can probably be done in 3 MHz using the same methods proposed for efficient 6-MHz ATV. We do not advocate this scheme, as it raises many questions that should be examined carefully. We simply present the possibility of doing this.

92-93. *Special cases.* We agree that certain major markets must be examined on a case-by-case basis to find the best solution.

95. *Spectrum comments.* See Section 3. If spectrum efficiency is the goal, then NTSC must be phased out eventually.

97. *CNR for ATV relative to NTSC.* In general, efficient ATV systems can manage with *lower* CNR than NTSC.

98. *Transponder bandwidth required for ATV.* The Adaptive FM system developed at MIT permits a 12 MHz baseband in a single normal transponder channel with the same power, and results in the same SNR in the received signal. See Appendix 6.

115-119. *Flexibility.* We advance the OAR as a means of incorporating flexibility in any standard-setting procedure. See Section 5. As mentioned in the comments, EIA did not reply at all to the comments I made with respect to their objections. I believe their objections to the OAR are without merit.

120. *When to adopt standards?* The Advisory Committee has set up what amounts to a selection procedure for proposed systems that will take at least 18 months to complete. The staff of the Commission could themselves examine what is known about the proposed systems and put together a proposal for comments. The question of D/U ratios required for finding extra spectrum has only recently surfaced, and so most of the system proponents have not had a chance to deal with this in their system design.

If the staff feel, at some point, that they can specify a system that meets the long- and short-term goals and seems acceptable to the industry (excluding the system proponents) then many companies would probably be agreeable to supplying the equipment.

122-1. *Is an ATV transmission standard desirable?* Yes, but it does not have to be fully specified. With a modicum of 'intelligence' in the receivers, a range of standards could be accommodated and some experimentation encouraged. The matter of actual performance under typical conditions seems very important.

122-2 *Too early for standards?* Yes. We must have evidence that the proposed system actually works. Further study is required to establish just what D/U ratios are needed to get the desired station assignments. Then the proposed systems can be tested for compliance.

122-3 *De facto standards?* Such will not be adopted unless there is incentive for the parties to do so. See Section 4.5. If there were a perceived advantage to the parties to adopt such a *de facto* standard, they ought to be able to adopt a good one. However, the matter should not be left entirely in the hands of the industry. The public deserves better from the Commission.

122-5. OAR as an alternative to standard setting? See Section 5. We do not advocate the OAR as an excuse to avoid setting standards. It could be used to make the process more flexible since the standards could allow some room for experimentation.

126-1. *Receiver compatibility automatic?* ABC and NBC would provide compatibility and CBS might not, according to their original comments.
126-2. *Specify the quality of compatible pictures?* The Commission does not specify the quality now and it is often disgraceful. Providing good quality under compatibility constraints is harder, particularly when the aspect ratio problem is considered.
126-3. *Effect of low-cost converters.* Rather than not requiring compatibility after a period of time, the Commission should affirmatively decide when NTSC is to be phased out. If cheap converters become available, that will permit viewers to continue to use their old sets after the demise of NTSC, which no doubt would cushion the blow.

129-130. *Baseband inputs.* I fully support this idea, but, as discussed in 5.3, the multiport approach can only deal with different scanning standards by means of dedicated set-top converters, a more expensive and less desirable result than the OAR. Furthermore, standardizing a specific scan format for the display, which is required to make the multiport approach wisely useful, is an unnecessary restriction that will unduly hamper the development of high-quality receivers. The same can be said for a multisync requirement. This will raise the cost of every receiver, and still not be able to accommodate the wide range of sweep frequencies bound to be found in tomorrow's receivers.

131. *The OAR.* I do not recall ever saying that signal compatibility would be completely unnecessary with the OAR. The OAR could readily be made adaptable to a certain *range* of signal formats but not to every conceivable format. That is a silly idea that was never advanced by anybody but the EIA, which used it as a red herring. The EIA representative was unable to refute a single statement I made in rebuttal of its letter. Since there are no American-owned electronics companies in the Consumer Electronics Group of the EIA, I believe its opinions should carry little weight with the Commission.

133. *Automatic ATV compatibility in alternative media?* I believe the Commission is engaging in wishful thinking on this point. These media will do what they believe to be in their economic interests. Those who want to deliver a special service will want to be as different from terrestrial as possible, and not as similar as possible. Certainly the DBS people will feel no urge to use what others are using. There is no sign of such a move among the possible parties, except for the multisync/multiport proposal.

134-1 *Compatibility in ATV desirable?* What is not only desirable, but essential, is that a single receiver should be able to deal with NTSC and all the ATV formats. The viewer doesn't care how this is accomplished. I have proposed the OAR for this purpose, together with the possibility of a friendly family of ATV systems for the various media based on subband coding. See Section 4.5.

134-2,3. *Voluntary standards?* That might be nice, but there is no sign that this is happening. As mentioned previously, there might be agreement on a friendly family of standards, all receivable on the OAR, but such a proposal will not originate with the various media, as it is not in their individual interests to do so.

134-4. *If the Commission feels that it is necessary to regulate VCR's in the public interest,* and does not find in existing laws the necessary authority, it can ask the appropriate Committees of the Congress to give it the authority. It appears that the Congress is very sensitive to the economic implications of HDTV, and if an argument can be made that such regulation would improve the prospect of a vigorous ATV development with substantial US participation, then I think the Congress would be very responsive.

TAB

Reliable EDTV/HDTV Transmission in Low-Quality Analog Channels

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Abstract

The presence of random noise, interference, multipath, and imperfect frequency response in terrestrial broadcasting channels, and of pervasive low-level reflections in cable systems, degrades the quality of most television reception. These effects tend to reduce the difference in quality between that of NTSC and that of various advanced television systems, as actually delivered to the home via such channels. In this paper, several methods are presented to deal with these effects, and thus to preserve the improved quality made possible by currently proposed EDTV and HDTV systems. Automatic channel equalization is used for first-order correction of multipath and frequency distortion. A scrambling method is described that transforms all remaining degradations to additive random noise, which, for a given noise power, is of minimum visibility. Random noise, whether additive or produced by scrambling of other defects, is suppressed by adaptive modulation of the various signal components. If the channel CNR is high enough, some digital data can be transmitted in addition to the analog signal by a method called "data under." The methods are applied to a receiver-compatible system that utilizes a very low-power 3-MHz augmentation channel as well as to a bandwidth-efficient 6-MHz system that is not receiver compatible. One version of the latter system can be operated at such low CNR that it may be possible to utilize the taboo channels.

Introduction

This paper deals with the transmission of television signals through the analog channels normally used for this purpose, including terrestrial transmission in the VHF and UHF bands, coaxial cable, satellite transmission, and fiber-optic cable in the analog mode. It also relates to analog recording systems using tape, disk, etc. In all of these media, the received signal usually suffers loss of quality due to random noise, interference from other transmissions, multipath (echoes), and frequency distortion. This is so much the case that in broadcast television, for example, the image quality seen on home receivers is vastly reduced as compared with that produced in the studio. Reducing or eliminating these effects is especially important in high-definition TV, since channel defects might easily negate the higher resolution of which these systems are capable.

In terrestrial broadcasting, the signal-to-noise ratio (SNR) in the image is a function of the effective transmitted power, the spacing between transmitter and receiver, the effectiveness of the receiver antenna, and the quality of the circuitry in the tuner. All of these factors are limited by economics. Interference relates to the spacing between transmitters, to the antenna, and to the selectivity of the receiver circuitry. It is desired to have as many stations as possible, and the other factors are again limited by economics. Echoes due to multipath conditions can be partially suppressed by expensive antennas, and so are also governed by economic considerations. The channel frequency response is a function of transmitter and receiver filters, antenna characteristics, and the quality of the tuner circuitry — again economically limited.

In cable, SNR is determined by cable loss as compared with amplifier power and spacing. Pervasive microreflections result from improper terminations. The channel frequency response is affected by limitations similar to those found in broadcasting.

In principle, automatic equalizers can be used in receivers for the purpose of reducing echos and frequency distortion. [1] Some noise reduction is possible using frame-recursive temporal filters, although these are rather expensive for consumer use. [2] Another method of noise reduction that is quite simple is called coring. [3] It is used in VCR's but produces considerable distortion. More sophisticated methods have been widely studied in the laboratory, but have not been applied to practical TV transmission because of cost and limited effectiveness. [4] Some noise-reduction methods are employed in tape recorders. [5]

An additional factor not always considered in rating television systems is interference performance — both the degree of interference caused to other signals and the ability of the signal to deal with interference received from other signals. The methods developed here permit the design of systems with much higher performance than conventional systems in both respects. The improved interference performance can be used to permit closer transmitter spacing, as recently proposed by Zenith. [6]

For noncompatible systems such as are likely to be used for HDTV in cable and similar media or for an eventual bandwidth-efficient system for broadcasting, these methods can be used for all of the signal components that are free of dc. For receiver-compatible HDTV systems, the methods are useful primarily for the enhancement components. For systems that hide the enhancement data within the NTSC signal, the visibility of the extra information can be reduced. For systems that use an extra 3 or 6 MHz for enhancement, the transmission can be at such low power that channels not now useable can probably be used without interfering with existing NTSC stations.

Principles Used

We have found that it is possible to alleviate the quality loss due to channel defects by using a combination of the following methods.

Subband coding. In this class of methods, the 3-dimensional spectrum of the video signal produced by a high-quality camera is divided into spatiotemporal components. Each component is selected by a filter, preferable separable. That means that a cascade of three 1-dimensional filters — vertical, horizontal, and temporal — is employed. The components are time-multiplexed for transmission, each component being independently processed, for example by a static nonlinear amplifier and by an adaptive modulator. [7] At the receiver, each component is demodulated and interpolated, and then all the components are added together to produce the reconstructed video signal. The advantage of this technique is that the signal power is concentrated in just a few of the components, and that the perceptually more important components can be selected for transmission, adaptively, if desired. Each component can be treated appropriately according to how it is perceived. For example, the higher-frequency components do not require as high a SNR as those at lower frequency.

Adaptive modulation. It is the nature of television images that they depict objects of varying sizes, most much larger than a single picture element (pel). Thus, most of the pels in an image are located in the interior of objects and many fewer at the edges, where the video signal changes substantially from pel to pel. Because of spatial masking, the human visual system is much more sensitive to noise in the relatively blank areas within objects than in the busy areas at the edges of objects or where there is a great deal of fine detail. It is just in these relatively blank areas where all the signal components (except the one containing the dc level and the low spatiotemporal frequencies) are quite small. These small signals can be greatly increased for transmission and correspondingly reduced, along with the noise, at the receiver. Adaptive modulation thus greatly reduces the noise of whatever origin in just those areas where it would be most visible.

The efficacy of adaptive modulation is highest for those signals that are very small in the blank areas — namely the high-frequency signals. The dc and low-frequency RGB signals (or the luminance/chrominance signals, in an L/C system) do not have this property. Hence some other method of noise reduction is preferably used for those components.

Digital transmission. It is well known that noise of all kinds can be essentially eliminated in most cases by digital transmission, such as is used in some fiber-optic transmission lines and in certain disk-recording systems. Error correction can be used, if desired, for further noise immunity. Digital transmission is not used for normal TV because it would require a very large increase in channel bandwidth. While digital TV is hardly a new idea, it has special advantages and few disadvantages when used here.

FM transmission. Frequency modulation is another method of improving SNR by using a wider bandwidth. It is used in satellite transmission, where wide bandwidths are available. A narrow-band form of FM is also used in magnetic video recording to reduce the effect of unwanted changes in signal level. It is not used in normal TV transmission because of the wide bandwidth required.

Adaptive equalization. Adaptive equalization was first widely used for digital transmission in telephone lines [8] in order to permit transmission at a higher rate than would otherwise be possible. It is planned for some advanced television systems but is not yet in widespread use. The general idea is to transmit, along with the video signal, a test signal that is used to measure the channel frequency response. A correcting filter is then automatically derived to make a best-possible correction, according to some criterion that normally would be concerned both with frequency response and SNR.

Echoes due to multipath transmission can be modelled as frequency distortion, so that automatic equalizers also correct for echoes as long as the impulse response of the correcting filter has a long enough extent in time to encompass the echos.

Another channel degradation that can readily be corrected is nonlinear distortion. For this purpose a step signal comprising perhaps 16 levels ranging from zero to some maximum value is transmitted once per frame. The values of these levels as received are measured and a compensating nonlinearity computed and impressed on the received signal.

Scrambling. If an image is stored in digital form at both transmitter and receiver, which is likely to be the norm in advanced television systems, then transmission can be thought of as reading the contents from the transmitter store and replicating them in the receiver store. Normal transmission would involve reading out the data pel by pel and line by line in the usual raster-scan format and recording it in the corresponding storage locations in the receiver. However, this could be done in any order, including random order. As long as each storage location is read exactly once during the period devoted to transmitting one frame, and as long as the correspondence between transmitter and receiver storage locations is correct, accurate transmission would be effected. Note that once an image is entered into the receiver store, it can be read out in raster format to produce a normal video signal for display on the picture tube.

The "Data-Under" Method. The higher-frequency components of a video signal do not require as high a SNR at the receiver as do the lower-frequency components. With carrier-to-noise ratios (CNR) high enough to produce good pictures in NTSC — 40 db or so — adaptive modulation results in excess SNR for these components. In that case, extra channel capacity is available for transmission of unrelated digital information. This can be done by reducing the amplitude of the analog highs signal and adding it to a second digital signal of, say, one or two bits/sample. If the amplitude of the analog signal is well under the level spacing of the digital signal, the two can be recovered independently.

The amount of extra data that can be transmitted in this way is very large. For example, a 4-level signal, representing 2 bits/sample, can be hidden under an analog signal that has been reduced by a factor of at least 4, or 12 db. For a 6-MHz channel in which one-third of the capacity is used for the lows, this comes to 16 Mb/sec. In actual practice, this rate probably would have to be reduced somewhat. Even using only one sample per cycle — half the Nyquist rate — and one bit/sample would provide a capacity of 4 Mb/sec. Particularly in cable applications where the CNR at all receivers exceeds a certain minimum value, this extra capacity could be used for many different purposes. In broadcast applications, however, the result would be a loss of reception in those fringe areas where the CNR falls below the values required for proper separation of the two signals.

Combining the Methods

The system discussed here consists of several different combinations of the methods described above. When these methods are used together in the right way, it becomes possible to achieve very high image quality in the presence of substantial defects in channel performance. Images that otherwise would show poor SNR, an annoying degree of interference and frequency distortion, and multiple large-amplitude echoes, can be rendered with good quality and with very little expansion of bandwidth.

It is obvious that adaptive modulation of the kind described has the effect of reducing the noise and interference in blank areas by an amount equal to the adaption factor. Scrambling has several effects, and, in combination with adaptive modulation, is capable of greatly improving picture quality.

Echoes are dispersed as random noise. Since successive samples in the transmitted signal do not represent adjacent pels in the image, echo samples are dispersed to random locations, and thus appear as additive random noise and not as shifted images. The rms value of the resulting noise is simply the rms value of the echo, which may be considerable. Therefore, this technique works best with the high-frequency components, which have quite low power.

The use of adaptive modulation before scrambling has a remarkably beneficial result. This comes about because, in typical pictures, there are many more pels in relatively blank areas than associated with edges or areas of high detail. A typical pel is multiplied by one adaptation factor at the encoder and divided by another at the decoder. For pels in the main image, these factors are identical, so that there is no change; only the additive channel noise is reduced. For pels in the scattered echo, the first factor is small (near unity) for edge pels and large for blank-area pels. For pels that end up in blank areas, the second factor is large, while for those that end up in busy areas, the second factor is small. The most important case is that of the edge pels that are scattered into the blank areas; those are greatly reduced in amplitude. Thus, the energy in the scattered echo is greatly reduced as well as randomized. There is some increase in noise in the busy areas, but here its visibility is partially masked.

Frequency distortion is also dispersed as random noise. Echos can be modeled as a result of linear filtering, and since scrambling disperses echoes, it also disperses the effects of any other linear filtering operation such as frequency distortion. The latter can be thought of as having the effect of spreading some of the energy from each picture element into neighboring pels. This reduction in value of the current pel and a corresponding change in value of nearby pels can be thought of as a localized noise or close-in echo. With scrambling, the pels into which the energy is spread are not neighbors, but are randomly located in the image. Thus, *the effect of scrambling on a signal transmitted through a channel whose frequency response is not perfect is to produce a noisy signal completely free of frequency distortion.* If there were a great deal of distortion, the noise would be unacceptable. However, applied to the highs signals that have low average power, and used with an adaptive equalizer that partially corrects the channel distortion, scrambling completely eliminates the remaining distortion with acceptable noise level. Again, the distortion-induced errors that are scattered into blank areas are greatly reduced by adaptive modulation.

Interference from other signals is dispersed as random noise. It is clear that any noise is randomized by scrambling and reduced in the blank areas by adaptive modulation. This greatly decreases the visibility of interference from other video signals. In addition, each scrambled signal looks like noise to all other signals, scrambled or not, while, to an unscrambled signal, a scrambled signal looks like noise — both highly favorable results.

Since these favorable results can only be obtained with high-frequency components that are small in blank areas, the signal components that do not have this property must be noise-reduced and freed of frequency distortion by other methods, of which the most appropriate is digital transmission. While digital transmission requires additional channel capacity, the penalty is not so great in this arrangement since only a very small proportion of the original video signal must be so treated. Most of the signal can be transmitted with no bandwidth expansion at all by the methods described herein.

A Bandwidth-Efficient Channel-Compatible System

Receiver compatibility is not required for use in cable or other nonbroadcast applications, and in that case, all of the methods listed can be freely used to design a system with maximum quality for the bandwidth and power available. Such a system could ultimately be used for broadcasting as well, in which case it would not only give much higher quality than NTSC within the present 6-MHz channels, but also would have better performance under the (typical) degraded channel conditions.

Systems having such good performance at low CNR's raise another interesting possibility, as recently pointed out by Zenith. [6] Since the system results in much higher quality at a given SNR than NTSC, it is possible to operate at much lower ratios of desired to undesired signal levels. It may therefore be possible to transmit independent EDTV signals in the existing taboo[1] channels at such low power that no unacceptable interference would result.

The Encoder

As shown in Fig. 1, a video signal, received from a TV camera, VTR, or production system, is digitized and passed to the filter bank, which separates the signal into a number of spatiotemporal components. Those containing a dc value (the "lows") are separated from those that do not (the "highs".) The former typically are red, green, and blue video signals representing the dc and low spatial- and temporal-frequency components that cannot advantageously be adaptively modulated. These are transmitted to the preprocessor, where they are combined with audio and data signals that are to be transmitted along with the image signals, and subjected to a coding process, preferably implemented digitally. The objective of the coding process is to prepare these signals for digital or FM transmission using the smallest amount of data feasible considering the quality of the analog transmission link to be employed. Any known method of encoding may be used, such as pulse-code modulation (PCM), differential PCM, transform coding, vector coding, etc. In the case of FM, the encoding process is preferably implemented

[1] A "taboo" channel is one that cannot be used at present in a given city because of interference with existing NTSC stations.

digitally, resulting in a digital data stream that, when put into analog form, becomes a correct frequency-modulated signal.

The lows components produced by the filter bank and that do not contain a dc component, are processed in the adaptive modulator so that their levels are generally made as high as possible without channel overload. [9] In that method, x, y, t signal space is divided into blocks, e.g., 4x4x4 pels in size. Within each block, an adaptation factor is found. The block factors are transmitted to the receiver in the data channel. At both transmitter and receiver, the factor actually used at each pel is found from the block factors by interpolation, so that the used factor varies smoothly from pel to pel, thus avoiding block effects.

The adaptively modulated highs components and the other processed components are entered into the store, which holds at least one frame of information, via the multiplexer. The components that are used and the locations where the data is entered are selected by the multiplexer under direction of the control unit and address generator. All the signals to be used in one frame must be stored and read out for transmission within one frame duration.

For transmission, data is read out of storage in two related data streams and converted to analog form. The two signals are then quadrature modulated onto a single carrier. The transmitter is simply a frequency shifter and linear video amplifier, as it is essential that the emitted signal be a faithful frequency-shifted version of the encoder output signal.

In the case of signals intended for transmission in the usual 6-MHz TV channel, the output signals from the store are each nominally 6 Megasamples/sec, so that the bandwidth of each analog signal is 3 MHz.

Scrambling of the data is achieved by generating a suitable sequence of addresses in the address generator during the readout process. A pseudorandom rather than a truly random process is desired, since the sequence of addresses must be known at the receiver. Well known techniques may be used for this purpose. It has been found that a simplification is possible in the implementation of the scrambler. Sufficient scrambling is obtained if the column addresses are pseudorandomly shuffled independently of the row addresses. Thus the rows may be read out at random using randomly rearranged column addresses.

For minimum visibility of the noise and for encryption purposes, it must be possible to choose the random sequences used on successive frames arbitrarily from a large repertory of possible sequences. Since each sequence can be characterized by a very short generating function [10] all that is required to accomplish this is to label each sequence with a number, to store a table of numbers and corresponding generating functions at both encoder and decoder, and to transmit in the data channel, for each frame, the number designating which sequence is used. Alternatively, the randomized starting address of a single random sequence can be stored in the table. The table itself may be changed from time to time for encryption purposes.

A close relationship is desirable between the two signals to be quadrature modulated so that, in case of a phase error in demodulation, a relatively minor effect on the image will result. This can be accomplished by dividing the store into two units (at least conceptually), each containing the data from half of the scanning lines, interleaved. Readout from the two halves of storage is identical, so that vertically adjacent picture elements are transmitted simultaneously by the two channels. Demodulation errors therefore manifest themselves as crosstalk between vertically adjacent pels, which results in a small loss of vertical resolution.

The Decoder

Referring now to Figure 2, the operation of the decoder can be explained. The radio-frequency signal picked up by the antenna or transmission line is passed through a tuner, which preferably shifts the spectrum of the selected transmission to as low a frequency range as possible. For example, in a 6-MHz transmission, this range might be 2 to 8 MHz. The resulting signal is digitized and passed to a digital detector, which recovers the two 3-MHz baseband signals originally impressed on the carrier, but corrupted by channel effects. These signals are input to the automatic equalizer, which compensates for the frequency response of the channel as well as any nonlinear distortion as discussed previously.

The corrected signals are entered in the store in the locations determined by the address generator, supervised by the control unit. It is at this point that descrambling is performed, and for this purpose, the particular pseudorandom pattern in each frame must be known to the control unit. From the store, the signals are read out from the locations determined by the address generator. The demultiplexer separates the data corresponding to the dc and low-frequency components from that corresponding to the high-frequency components. The former are decoded by the processor to produce the lows component and the audio/data signal. The latter are decoded by the demodulator and then interpolated in the filter bank to produce the various high-frequency components. The highs and lows are now added together to produce the video output signal, which approximates the system video input.

A Numerical Example of a Cable System

Where compatibility and interference are not problems, and it is desired to achieve the best possible performance under a variety of conditions, it is clear that the audio, the adaptation information, and the low-frequency components (including chrominance) must be protected to the greatest extent. In such systems, it appears desirable to transmit these components digitally. Using one bit per sample, it should be possible to transmit at least 6 Mbits/sec and possibly as much as 12 Mbits/sec in the "data-under" channel. This information would be essentially noiseless. The highs components should be substantially free of the effects of channel all degradation, including noise, at a CNR of about 36 dB.[2]

[2]The CNR values quoted in this paper are conservative. We have not completed our study of this matter. It is possible that even lower values will prove feasible.

An analog signal of 6 MHz bandwidth added to the 2-level digital signal is equivalent to 12 Megasamples/sec. If 20 components are used, each at 12 frames/sec as shown in Fig. 3, each such component can use 600 Kilosamples/sec and thus has a resolution of 166 pels/picture height high by 300 pels/picture width wide. The resulting luminance resolution ranges from 664x1200 at 12 fps to 166x300 at 60 fps. Chrominance is 166x300 at 12 fps. The resolution at 36 fps is 332x600, substantially higher than NTSC.

A Numerical Example of A Low-Interference System

Where it is desired to transmit in the taboo channels of the UHF and VHF bands without causing unacceptable interference to existing stations, the scheme proposed by Zenith can be used. In that scheme, all nearby stations are synchronized at least well enough so that their vertical blanking intervals are simultaneous. The digital components are transmitted as multilevel signals in this interval, while the analog highs signals are transmitted at very low level during the active portion of the NTSC fields. Assuming that the audio and lows components could be transmitted in, say, 10% of the field time, the resulting linear resolution would be about 5% less than in the example quoted above. No more than 24 db SNR, possibly less, would be required for essentially noise-free reception.

A Receiver-Compatible System Using a 3-MHz Augmentation Channel

Systems of this type have been proposed by Glenn [11] and North American Philips. [12] Their advantage over systems that hide enhancement information within the NTSC signal is that the signal is completely unaltered, guaranteeing perfect compatibility. Of course, more channel space is required. The methods discussed above permit a substantial quality improvement with a very low-power auxiliary channel, and can be used in any kind of advanced television system using an augmentation channel.

As shown in Fig. 4, the NTSC luminance bandwidth is limited to 3 MHz and the chrominance bandwidth to .6 MHz. While this may reduce resolution slightly on today's high-end receivers, it completely eliminates cross effects and provides a good base signal for enhancement. The spectral components in the larger shaded area can be transmitted in 3 MHz at a rate of 15 frames/sec and those in the smaller shaded area at 30 frames/sec, giving about MUSE quality. About 24 db CNR, possibly less,[3] is required to make these components appear virtually noise-free when adaptive modulation and scrambling are used.

At a somewhat higher CNR of about 36 db, we believe that it will prove possible to superimpose these enhancement components on a 2-level digital signal and achieve an additional transmission rate of at least 3 Megabits/sec. This would permit a very high quality audio signal to be added, as well as a large amount of data. Of course, the digital channel could also be used for additional resolution enhancement.

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[3]We have done this at 16 db CNR in laboratory simulations.

Note that the overall response of the compatible system is slightly inferior to that of the noncompatible system in spite of the fact that the former uses 9 MHz overall and the latter uses 6 MHz. In addition, the noncompatible signal may be used at low CNR, while in the compatible system, a low CNR can be used only for the augmentation channel. The NTSC channel requires the usual good CNR for good-quality pictures. This shows the high price that must be paid for NTSC receiver compatibility.

We have already demonstrated that it is possible to reduce the frame rate of chrominance to 15 fps without causing any perceptible effect. [13] The resulting spectral "hole" can be used to double the horizontal chrominance resolution, a highly desirable result.

Demonstration

In the oral presentation of this paper, a video tape was shown illustrating the recovery of good quality pictures from a transmission degraded by multipath of -8 dB, frequency distortion, and additive random noise at a CNR of 16 dB. An example is shown in Fig. 5.

Conclusion

We have described a group of methods that can be combined to achieve very high efficiency in transmitting video signals at low power in imperfect analog channels. When combined with subband coding, they permit transmission of excellent EDTV images with digital sound in a 6-MHz channel, either in cable or over the air. Since the required power is so low, tt may be possible to utilize the taboo channels without causing undue interference to existing NTSC stations. The methods are also very effective for transmitting enhancement signals in receiver-compatible systems. In that case, it is highly likely that a very low-power 3-MHz channel would be sufficient to supplement NTSC sufficiently to achieve performance comparable to any of the currently proposed EDTV or HDTV transmission systems.

This research has been supported since 1983 by the members of the Center for Advanced Television Studies, and since 1987 by an additional contract from Home Box Office, one of the CATS sponsors, for high-efficiency noncompatible systems. The work reported here has, of course, been done primarily by our students, of whom Adam Tom, Ashok Popat, and William Butera contributed the most. We gratefully acknowledge the contributions of sponsors, students, and colleagues.

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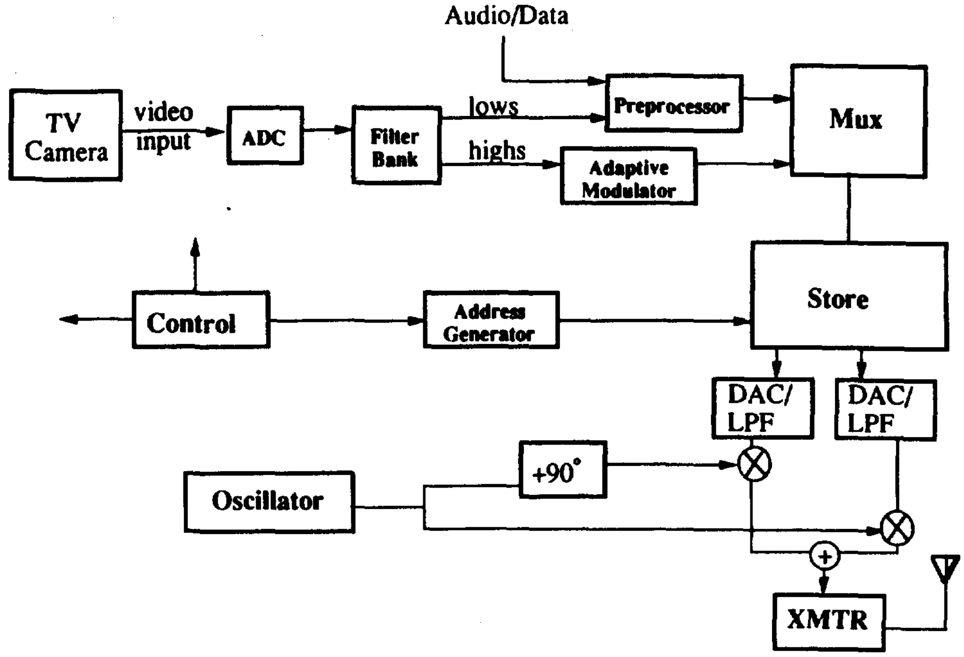

Figure 1. Encoder for a Bandwidth-Efficient Channel-Compatible System
The input signal is digitized and divided into components. Adaptive modulation is used for the highs and a digital representation for the lows, audio, and data. The components are selected, stored in raster order, the highs read out in scrambled order and the lows in normal order, converted to analog form, and then modulated in quadrature onto a single carrier in the middle of the band.

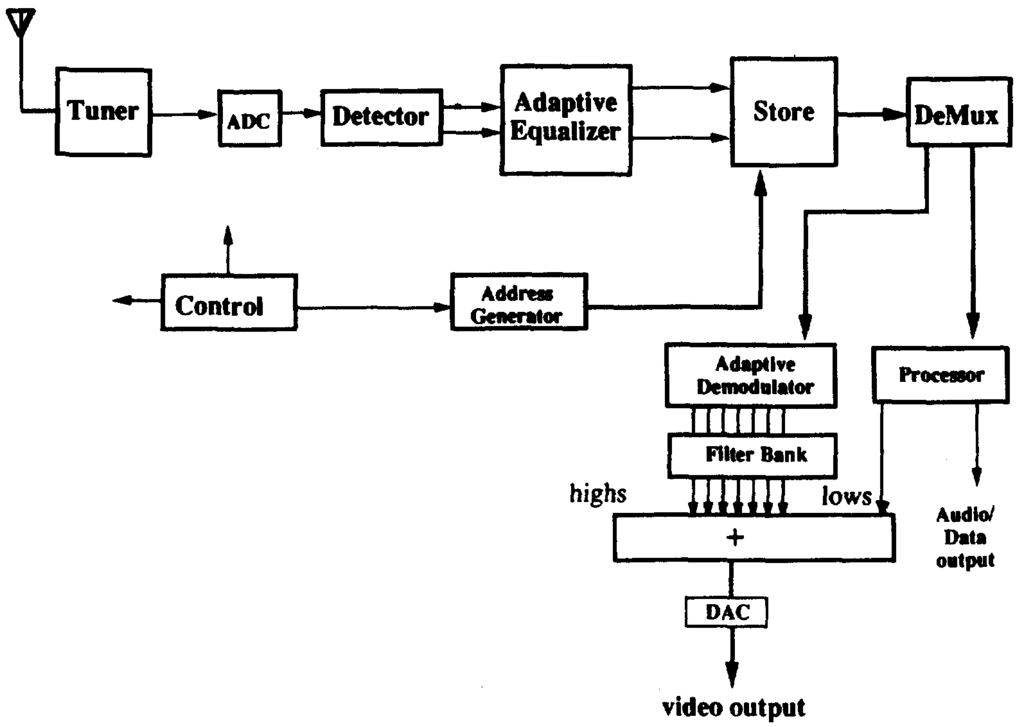

Figure 2. Decoder for the Same System
The received signal is shifted to a low intermediate frequency, digitized, and detected. After adaptive equalization, the data is entered into the frame store in the same order (scrambled for the highs) in which it was read out at the encoder. The store is read out in raster order and then the highs and lows/audio/data are appropriately processed, adaptive demodulation being applied to the highs. Lows and highs are added and converted into analog form for the final output.

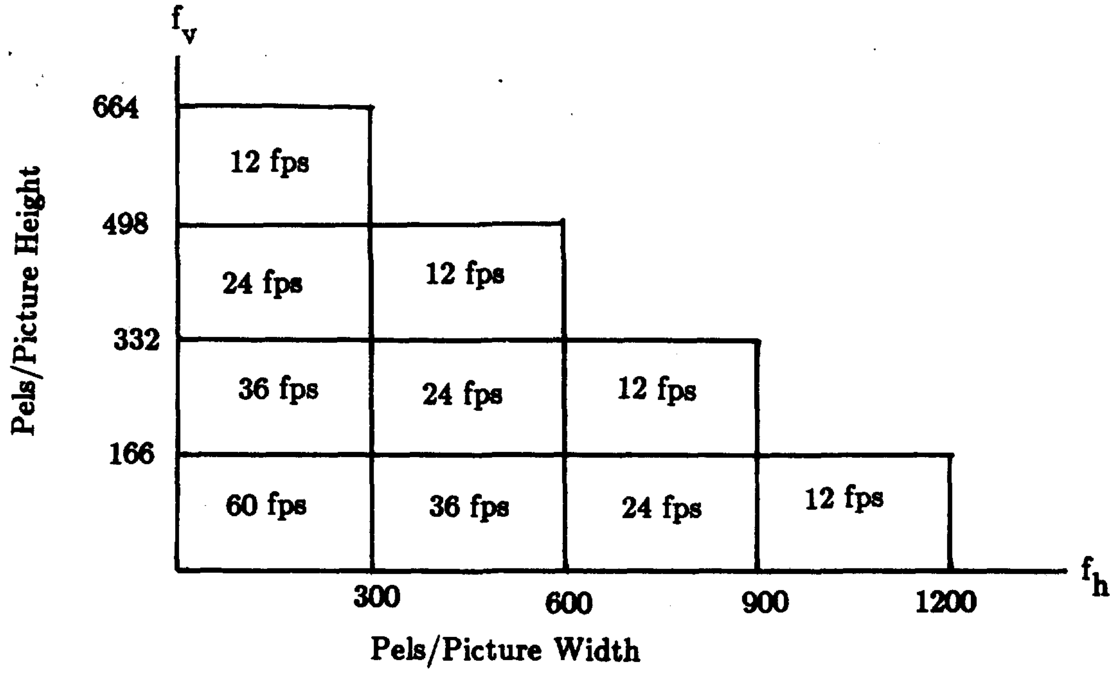

Figure 3. Spatial-Frequency Response of a Cable System
The luminance spatial-frequency response ranges from 664x1200 at 12 frames/sec to 166x300 at 60 fps. The chrominance response is 166x330 at 12 fps. A different selection of components would be used for film. It is also possible to select components according to the degree of motion so as to have higher spatial resolution in scenes with little motion and higher temporal resolution in scenes with a great deal of motion.

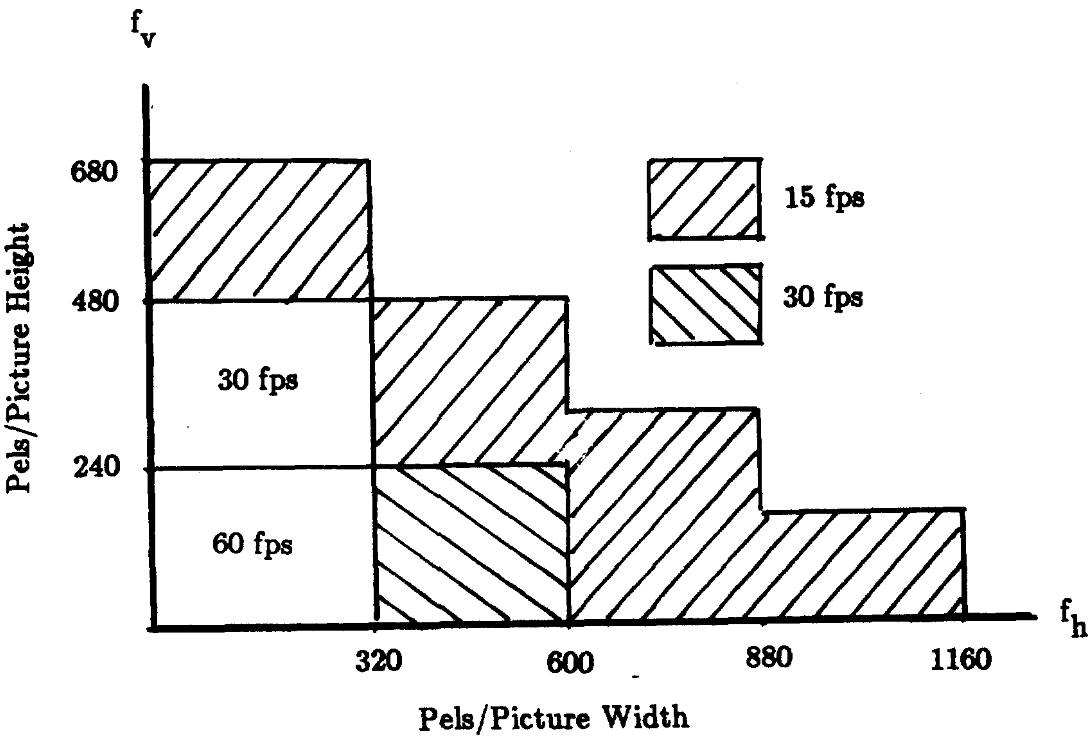

Figure 4. Spatial-Frequency Response of a Receiver-Compatible System
The NTSC signal is filtered so as to eliminate cross effects, giving a luminance response [illegible]0x320, here shown as 60 fps for the lower vertical frequencies and 30 fps for the higher vertical frequencies to symbolize the effect of interlace. The shaded areas show the enhancement components that are transmitted in the 3-MHz augmentation channel, some at 30 fps and some at 15 fps, raising the response to 680x1160 at 15 fps. The horizontal chrominance response is doubled by reducing its frame rate to 15 fps.

a

)

Figure 5. An Example of Reduction of Channel Degradation
Fig. 5a is the original, 280x450 samples. Fig. 5b is corrupted by an echo of -8 dB, additive random noise of -16 dB, and a certain amount of frequency distortion. Fig. 5c represents the system output when adaptive modulation and scrambling are used, as discussed in the text. It is assumed in this example that the low-frequency component has been transmitted digitally and therefore it was free of channel defects. The resolution and SNR of all the images has been reduced somewhat by the printing process.

TAB

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THE OPEN-ARCHITECTURE TELEVISION RECEIVER

The purpose of this brief note is to give a nontechnical description of the concept and to explain why we believe this is an appropriate kind of receiver to use in the Advanced Television Systems being considered for the United States.

All TV receivers consist of a tuner, a signal-processing section, and a display, including audio. In today's receivers, the middle portion accounts for 10-25% of the cost. Most of the cost is in the picture tube and associated hardware. In HDTV receivers, the display, at least initially, will account for the overwhelming portion of the cost. The main innovation of the OAR is to make the signal-processing section digital and programmable. (This is innovative only with respect to TV receivers; it is an increasingly common way to design complicated hardware today.) In addition, we have put as many tuner functions as possible into digital signal processing hardware. The display section does include a fixed upconverter to achieve a progressively scanned display with a high line and frame rate. At present, this is only found in a few high-end receivers, but is likely to be used in all ATV receivers, since it is now well known that this is required to produce the highest quality image from whatever is transmitted.

The use of programmable digital signal processing (DSP) rather than fixed processing (all ATV receivers will use at least some digital processing) raises the cost very little, if at all, and achieves important objectives not otherwise possible. In all likelihood, if a receiver must deal with two or more transmission standards, the OAR is the *cheapest* way to build it, in the time-frame of even the first ATV systems.

1. Such a receiver can be adapted to a range of ATV transmission formats at low cost, without obsolescence, and without set-top converters. It is therefore not necessary to wait until a perfect format is selected before launching an ATV service. All of the currently proposed formats could readily be accomodated in the OAR.

2. Image quality can be improved in an evolutionary manner over the life of the receiver by modifying the operating mode of the receiver or by adding plug-in modules. Any available headroom in the transmission systems can be utilized.

3. Such a receiver can readily be interfaced with VCR's, cable, fiber, DBS, optical disks, computers, video games, cameras, electronic still photographic equipment, interactive systems, people meters, addressing/encryption systems, and other devices not yet imagined. It does not complicate these other systems - it simplifies them since the computing power of the OAR can be used to facilitate the interconnection. No interface boxes are used. Most peripherals plug into one of the receiver busses, just the way computer peripherals plug into computer busses.

4. The open architecture facilitates the provision of software or hardware add-ons by third parties, such as picture-in-picture, image enhancement, freeze-frame, viewer-controlled zoom and pan, home video production systems, etc. Provision can be made for much better viewer control of color and tone reproduction, as is routinely done in graphic

arts. Of course, the original manufacturer can also provide these functions. In fact, this architecture makes it easy for the manufacturer to provide a large range of receivers for different market segments without complete redesign. For the top-end market, the three receivers sections could be offered as separate components.

5. A receiver with substantial processing power makes possible a much more flexible transmission system design. For example, in the MIT-CC system, we utilize a variable transmission frame rate, where we optimize the tradeoff between spatial and temporal resolution according to the subject matter, on a scene-by-scene basis. Eventually this can be done on a point-by-point basis within each frame.

The Input Section

The OAR requires only three input terminals: RF, baseband (3 wires), and digital. RF signals are converted to baseband and baseband signals are digitized and stored in a first step. All further decoding is done in DSP hardware and software, according to the particular transmission system being used.

The Computation Section

This section is, in fact, a signal-processing computer. It makes use of the cheap and powerful chips now being developed for computers. (If such receivers become common, they will be the largest consumers of such chips.) One of the main reasons for going to such a processing structure is to take advantage of the enormous investment being made in the development of such chips for other purposes. An important feature is the well defined busses, which permit designers to develop other devices that plug in very easily. A typical function of this processor is receiving information from the input frame store and then rearranging and interpolating it to the standard rates utilized in the display memory. It does this under supervision of the control module, which is programmed by a small amount of data transmitted along with the signal, or possibly by manual viewer control when using other input sources.

The Display Section

All receivers need not have the same line and frame rate on the display (progressive scan and as high line and frame rates as possible should be used) but all kinds of signals received, including NTSC, would be displayed at the same standard on any one receiver. The display section would include a frame store, (there is absolutely NO advantage for an ATV receiver not to use frame stores) fixed interpolation circuitry, and digital-to-analog converters. If desired, an RGB interface could be provided for foreign signals, but it would be much better to route those signals through the input section so that line- and frame-rate conversion could be done as required. It should be noted that this display is very similar to those used today in many computer graphics systems.

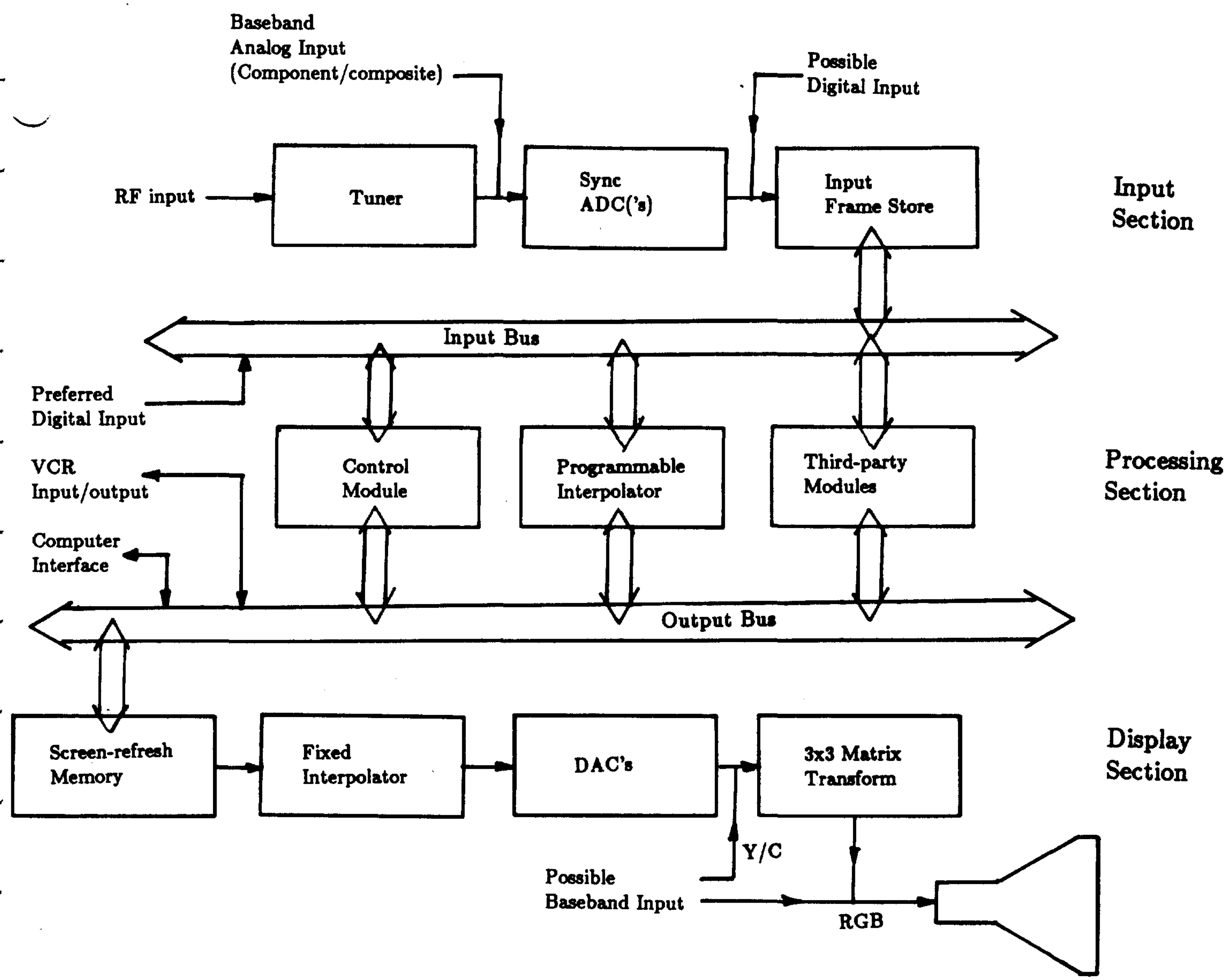
The OAR in a Multiple-Standards Environment

Based on long and extensive practical experience in the design of sophisticated electronic systems for production, it is my opinion that this type of receiver will be the *cheapest* as well as the most convenient way to build high-definition receivers that have to cope with multiple standards. It will be cheapest for the multinational manufacturer and therefore cheapest for the consumer. This results mainly from the fact that the OAR scan-converts all formats to a single display standard. The latter is *mandatory* for highest image quality in any system. Once this price has been paid, the standards conversion, implemented in low-level DSP hardware, involves ony a few special-purpose chips, and costs very little.

It is probably true that if a single worldwide standard could be agreed upon, a single-purpose receiver would be somewhat cheaper. However, this single standard would have to be fixed in all its details throughout its life, and the latter would have to be guaranteed to be 10-20 years in duration. In view of recent events, I fail to see how anyone can seriously believe that this will happen.

All ATV receivers will have to cope with at least one of the current standards - NTSC, PAL, or SECAM. There are likely to be several independent HDTV systems used by cable companies, such as HBO and General Instruments. ACTV is being pushed very hard. In addition, it would be a foolish manufacturer who would not also provide for MUSE capability, and possibly the European HDMAC system as well. Note that in the OAR, one merely *provides* for the capability, and does not implement it in every receiver sold. For installations that need the capability, the appropriate hardware or software module is plugged into the bus, as in a PC. No set-top converters are used.

All HDTV receivers will be expensive, certainly at the beginning, because of the picture tube, if nothing else. The OAR adds very little cost to these first sets, and ensures, to the extent possible, that both manufacturer and consumer will get maximum benefit from their investment for many years to come.



THE SMART OPEN-ARCHITECTURE RECEIVER. The input and display sections are fixed, while the the processing section, organized like a personal computer, is programmable under the control of a small amount of digital data transmitted along with the signal. This section could be upgraded by adding or exchanging software or hardware modules, some of which could be offered by third parties. In this example, the detector is incorporated into the processing section, rather than implemented in analog hardware in the "front end," in order to facilitate programmable detection of signals with multiple carriers, such as ACTV and the system proposed by North American Philips. Other configurations are possible in the display unit, which probably would use mixed highs or luminance/chrominance representation in the memory, rather than RGB.